How Can Climate be Predictable when Weather Isn’t?

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Weather Forecasting is Hard!

You learned about this in a University

- Air masses and fronts
- Convergence and divergence
- Vorticity maxima and shortwaves
- Quasigeostrophic lift
- Convective available potential energy
Weather vs Climate
what’s the difference?

• If you don’t like the weather:
  – *Wait five minutes!*

• If you don’t like the climate:
  – *Move!*

You learned about this in grade school
Climate is Place

*Location! Location! Location!*

- Depends on **where you live**:
  - Latitude!
  - Altitude (mountains vs valley)
  - What’s upwind (ocean vs land)

- Changes very slowly

- Very **predictable**

- We can *predict that Phoenix is warmer than Fargo* for precisely the **same reasons** that we can predict a *warmer future!*
Ever Wonder Why?

- **Day** is warmer than **night**
- **Summer** is warmer than **winter**
- **Miami** is warmer than **Minneapolis**
Heat Budgets
Climate Forcing & Forecasting

• If there’s a deterministic relationship between forcing and response

• ... and the forcing is strong & predictable

• ... then the response can be predictable as well!

• Examples:
  – Day vs night
  – Summer vs winter
  – Miami vs Minneapolis
  – El Niño / La Niña
  – “Little Ice Age”
  – Glacial-interglacial
  – 21st Century warming
Dancing Molecules and Heat Rays!

• Nearly all of the air is made of oxygen (O$_2$) and nitrogen (N$_2$) in which two atoms of the same element share electrons.

• Infrared (heat) energy radiated up from the surface can be absorbed by these molecules, but not very well.

Diatomic molecules can vibrate back and forth like balls on a spring, but the ends are identical.
Dancing Molecules and Heat Rays!

- Carbon dioxide (CO$_2$) and water vapor (H$_2$O) are different!

- They have many more ways to vibrate and rotate, so they are very good at absorbing and emitting infrared (heat) radiation.

*Molecules that have many ways to wiggle are called “Greenhouse” molecules.*

Absorption spectrum of CO$_2$ was measured by John Tyndall in 1863.
Solar radiation powers the climate system.

Some solar radiation is reflected by the Earth and the atmosphere.

About half the solar radiation is absorbed by the Earth’s surface and warms it.

Infrared radiation is emitted from the Earth’s surface.

The Greenhouse Effect

Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth’s surface and the lower atmosphere.
Fall Night in Colorado

6 AM surface temperature = -60 °C = -78 °F

4 inches = 10 cm

390 W m$^{-2}$

radiation emitted by soil
Fall Night in Colorado

6 AM surface temperature = 5 °C = 40 °F

radiation emitted by air
340 W m$^{-2}$

radiation emitted by soil
390 W m$^{-2}$

4 inches = 10 cm
The strongest evidence for the Greenhouse Effect is that we can survive night!
Common Sense

• Doubling CO$_2$ would add 4 watts to every square meter of the surface of the Earth, 24/7

• Doing that would make the surface warmer

• This was known before light bulbs were invented!

John Tyndall, January 1863
Common Myth #1

"Scientists confident about climate change because it’s been warming up recently"

WRONG!

We’re confident because we know that when we add heat to things, they warm up.
Cause and Effect

Forcing: Watts per square meter
Response: degrees Celsius or °F

Sensitivity = \frac{\text{Response}}{\text{Forcing}}

degrees per Watt m^{-2}
Learning from the Past

1. Geologic past
   (100’s of millions of years)

2. Deglaciation analog
   (18,000 years ago to preindustrial time)

3. Last Millennium analog
   (Medieval Warm Period to Little Ice Age)

4. Modern Climate Record
   (20th Century changes)

The further back we go, the less data we have to work with. Using modern data, we have only brief transients to study.
Ice Age World

Last Glacial Maximum 18,000 years ago

High albedo
Low CO₂
Over the past 420,000 years atmospheric CO$_2$ has varied between 180 and 280 ppm, beating in time with the last four glacial cycles.
Climate Forcing

Ice Age Climate Forcings

-3.5 ± 1

Forcing ~ 6.5 ± 1.5 W/m²
Observed ΔT ~ 5 ± 1°C

Implied Sensitivity: $\sim \frac{3}{4} \pm \frac{1}{4} \, ^\circ C$ per W/m²

Source: Hansen and Sato (2011)
Climate Sensitivity to enhanced CO$_2$

- Volcanoes, Last Millennium, Deglaciation all around 0.8 °C of warming per (W m$^{-2}$)
- Each doubling of CO$_2$ adds 4 Watts per square meter
- So expect about $(4 \text{ W m}^{-2}) \times (0.8 \text{ °C per (W m}^{-2})) = 3 \text{ °C per doubling of CO}_2$
Billions and Billions

Shanghai 1991 and 2012

• Currently 7 billion people on Earth but only 1 billion use lots of energy

• Rapid development to 4 billion energy users over coming decades

• Population growth only 30% but energy growth 300% by 2100
Climate Forcing

• If developing countries build modern economies based on coal ...

• Earth will gain more heat in 21st Century than it did when warming after Last Ice Age!

• ... but warming after Ice Age took 100 Centuries
How much warmer?

- **Land** vs ocean!
- **North** vs South

- Global mean warming of 2° to 5° C
- North American warming of 3° to 6° C

= 5° to 11° F

- Arctic warming of 8° to 14° F

Where is it 10°F Warmer
“on average?”

Denver ➔ Amarillo
Illinois ➔ Mississippi
Washington ➔ Tallahassee

Water? Crops? Real Estate? Health?
Bell Curves

- “Normal distribution” or “Gaussian”
- Average = Mean = Median = Mode
- “Standard deviation” $\sigma$ measures “width”
  - 68% of values fall within $1\sigma$ of mean
  - 95% within $2\sigma$ of mean, 99.6% within $3\sigma$
Means & Extremes

- People care more about extremes (tails) than averages
- Small changes in averages produce large changes in extremes
- Changes in the “spread” also produce changes in extremes
Historic Land Temps

Shifting Distribution of Summer Temperature Anomalies

Frequency of Occurrence

Temperature Anomaly (Standard Deviation)
Summer Temperatures

- Shift of mean by about $+1 \sigma$
- Increase in variability ($\sigma$) as well
- 15-fold increase in freq of temps that were at 99%-ile in 1970
**Heat Wave Statistics**

Figure 7.19 Characteristics of the summer 2003 heatwave in Europe.
(a) June, July, August (JJA) temperature anomaly with respect to 1961–90; (b) to (d) JJA temperatures for Switzerland; (b) observed during 1864–2003; (c) simulated with a regional model for the period 1961–90; (d) simulated for 2071–2100 under the SRES A2 scenario. The vertical bars in (b) to (d) represent mean summer surface temperature for each year of the time period considered; the fitted Gaussian distribution is indicated in black.

ΔT = 5 °C = 9 °F

2003

50,000 deaths

2 years out of 3

once in 10,000 years
What We Know for Sure

• Heat warms things up (100,000 BC)
• CO₂ absorbs and emits heat (1863)
• Each doubling of CO₂ adds 4 Watts/m² (1896)
• Climate can change (19th Century)
Very High Confidence

- Familiar climates:
  Warm summers, cold winters, warmer in tropics than poles, wet places & dry places

- Gradual but permanent warming of around 0.8 °C per Watt/m$^2$

- If China and India build industrial economies based on fossil fuel, CO$_2$ will double or triple

- That would add additional 4 to 6 Watts/m$^2$

- Eventual warming of global mean temperatures by 3 to 5 °C
Since the Ice Age

Modern warming will be comparable to warming after the Last Ice Age but 100x faster.
• More warming over land, in the NH, where it snows (around 60% more than global)
  8 °F to 14 °F in central USA
• Much more frequent “very hot” days
• More evaporative demand -- drought
• Shift toward higher precipitation intensity
• Some of the extra CO$_2$ will last for thousands of years after emissions stop
Uncertainty

• How fast economies will grow and adopt new technologies across the world
• Energy mix of developing economies
• Amount of water shortage in Central USA
• Rapid loss of ice sheets – fast rising water
• Rapid thawing of permafrost – fast rising CO$_2$ beyond FF emissions
Unknown

• Exactly how and when climate will change **locally and regionally**

• **Detailed impacts** on agriculture, insurance, financial markets, real estate, and economy in general

• Resulting changes in **social and political** environment

• **What people will decide to do** about all this!
From the Heart

• Simple
• Serious
• Solvable

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